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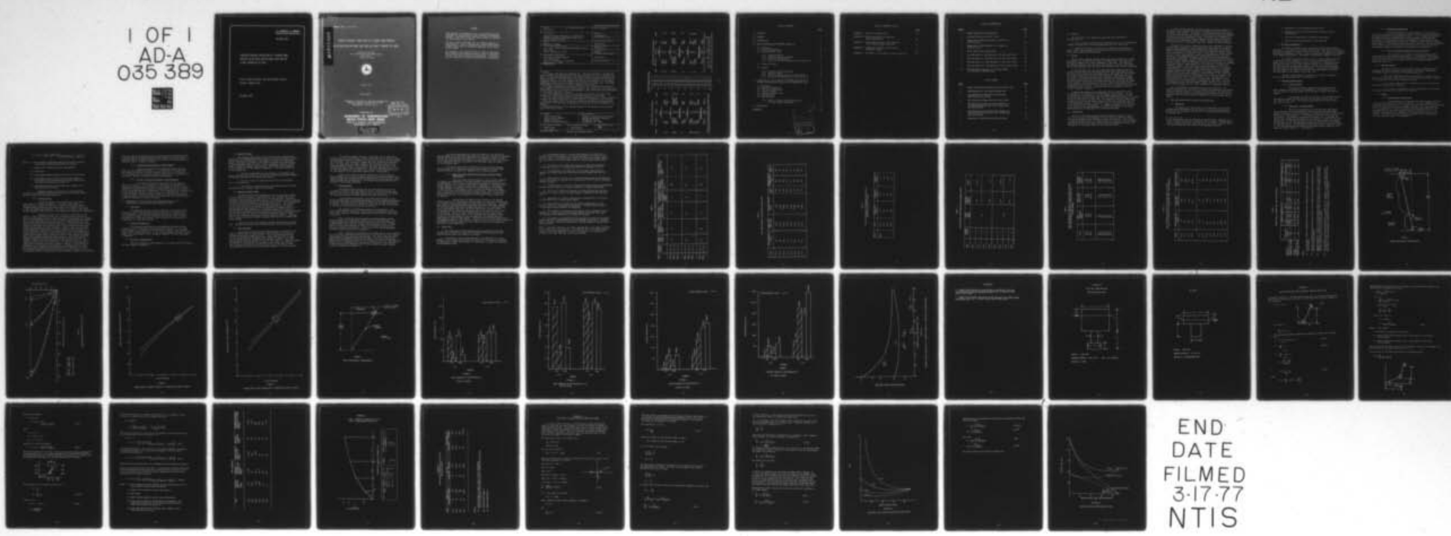

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COMPUTER MOORING SIMULATION OF A RUBBER BAND MOORING ON AN 8X26 NAVIGATIONAL BUOY AND AN 8-FOOT DIAMETER OSI BUOY

COAST GUARD RESEARCH AND DEVELOPMENT CENTER
GROTON, CONNECTICUT

OCTOBER 1975

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Report No. CG-D-110-76

COMPUTER MOORING SIMULATION OF A RUBBER BAND MOORING ON AN 8X26 NAVIGATIONAL BUOY AND AN 8-FOOT DIAMETER OSI BUOY

Kenneth R. Bitting
USCG Research and Development Center
Avery Point
Groton, CT 06340

October 1975

Final Report

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16. Abstract

The computer simulation was performed on a rubber band mooring to estimate the extent to which that mooring method can reduce the watch circle of a navigational buoy. The 8X26 navigational buoy and an 8-foot diameter OSI buoy were used in the mooring simulation. The 8X26 buoy is used because it is presently in the aids-to-navigation system; the 8-foot diameter OSI buoy is used because it is a low-drag lightweight plastic buoy that might be used in place of the 8X26 buoy. The rubber band mooring is compared to a one-inch diameter nylon mooring.

The rubber band mooring can reduce the watch circle of the 8X26 and OSI buoys when compared to that of the nylon slack mooring. The reduction in the watch circle is most apparent at low currents (approximately 1 knot) and becomes less pronounced as the current approaches 3 knots.

The 8-foot diameter OSI buoy shows a smaller watch circle on a rubber band mooring than the 8X26 buoy because of the reduced drag of the OSI buoy.

While the rubber band mooring increases the mooring tension, it does not appear to increase the sinker weight over that specified for a conventional chain mooring.

Using the results of the simulation, a method was developed for measuring the watch circle of the 8X26 buoy by measuring the angle at the top and bottom of the mooring.

Increasing pretension in the mooring (tension in the mooring at zero current) reduces the watch circle.

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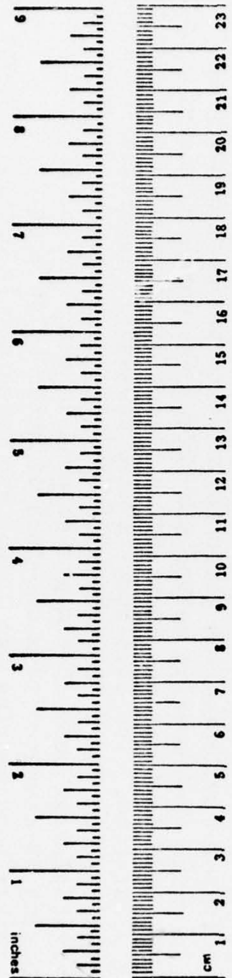
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

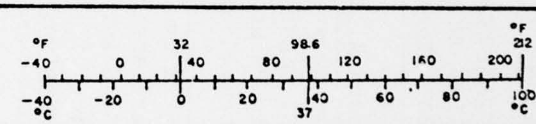
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1.0 OBJECTIVE

The objectives of the computer mooring simulation described in this report are to:

a. Provide mooring tension and buoy excursion data for use in designing a rubber band mooring for an 8X26 navigational buoy for a field test.

b. Establish the extent to which buoy excursion can be reduced by using a rubber band mooring and a low drag buoy (8-foot diameter OSI buoy) rather than a synthetic-fiber mooring.

2.0 SUMMARY

Using a static computer program, design data was developed for a rubber band mooring for an 8X26 buoy in support of field tests. The rubber band mooring is composed of six rubber filaments 27 feet long. The length of the inelastic section below the rubber band section is varied to determine the mooring pretension (the tension in the mooring at zero current conditions).

It was determined that the investigated mooring configurations can be used in currents less than three knots and water depth less than 125 feet. The shape of the mooring was investigated and it was found that the inclination (angle between the mooring and the horizontal) computed at the top and bottom of the mooring are not equal; therefore, the mooring is curved. An equation was derived from the design data that will determine the buoy excursion during field tests from the inclination at the top and the bottom of the mooring. The excursion of a buoy on a rubber band mooring can be extrapolated from one water depth to another with an accuracy of 15-20 percent (assuming constant current). Excursion cannot be extrapolated from one current condition to another.

A rubber band mooring and low-drag buoy (8-foot diameter OSI buoy) is compared to an 8X26 buoy on a nylon mooring (1 1/2:1 scope). For the cases analyzed, the excursion of the OSI/rubber band mooring is at least 73 percent and 23 percent lower than that of the 8X26 nylon mooring in currents of one and three knots, respectively. The tension in the OSI/ rubber band moorings is as much as 210 percent higher in the static condition than that of the 8X26/nylon mooring. The higher tension in the rubber band mooring is due primarily to the pretension. In a dynamic condition, it is expected that, because of the high compliance of rubber, the tension in the rubber band mooring will be less than that of the nylon mooring.

3.0 INTRODUCTION

As part of the Highly Elastic Mooring Development Program at the U. S. Coast Guard Research and Development Center, the use of rubber filaments for aids-to-navigation buoy moorings is under investigation. This concept is being developed for use in locations where a close watch circle is required (especially in high tidal areas) and/or high wave energy levels reduce the reliability or the effectiveness of other mooring methods.

A rubber band mooring made of rubber filaments used in parallel, is designed so that the bands are always stretched, even during periods of low tide or zero current. As current- or wind-induced drag forces develop on the buoy and mooring, the tension in the mooring increases and provides a lateral force that restrains the buoy. The greater the elongation at zero current (called pretension) the greater the restoring force and the smaller the buoy excursion. Rubber, being a highly compliant material, can easily stretch to accommodate high tidal changes and wave excursions.

During FY75, a series of laboratory tests were undertaken to subject several rubber compounds to static and dynamic loads with the purpose of establishing design limits and procedures for using rubber as a tension member. The results of that effort will be documented in another report. As an extension of the laboratory tests, it was desired to deploy a large buoy on a rubber band mooring so that the design procedures, materials properties, and deployment/recovery technique could be substantiated in actual field conditions. An 8X26 navigational buoy was selected initially. The rubber band compound (Compound 1202-S, Delford Industries) that showed the most promise, based on laboratory tests, had not been used in a mooring before and there was some question as to the ability to terminate the filaments reliably. After initial calculations showed that the 8X26, a high drag buoy, would exert a high load on the mooring, it was decided to first deploy a low-drag buoy using one filament of the new compound (Compound 1202-S) with four filaments of the rubber compound (Compound 1202-2) that had been used reliably in other moorings[1]. This procedure would test the new material with minimum risk to the entire system. The 8-foot diameter OSI buoy was used because it is a low drag buoy, it is of sufficient size that it could be a lightweight replacement for the 8X26 buoy, and it was available for deployment at that time. That buoy was deployed in July 1975 near Fishers Island, New York, in 42 feet of water; that deployment will be fully documented in a subsequent report.

With the deployment of the 8X26 buoy still the objective, the computer simulation was undertaken to estimate more accurately the mooring forces and mooring shape for the design of the mooring. The simulation results, combined with the current measurements collected at the test site coincident with the simulation, will provide for a more reliable mooring design.

4.0 8X26 NAVIGATIONAL BUOY MOORING DESIGN SIMULATION

4.1 Objectives

The objective of this portion of the simulation is to provide detailed design information for the design of a rubber band mooring for an 8X26 buoy as described in Section 3.0. Specific sub-objectives are to determine the:

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[1] A 6th class plastic buoy was deployed by the R&D Center, September 1973, using a rubber band mooring of Compound 1202-2 (natsyn). That mooring was still on station during the time this report was written (October 1975). The same compound has been used by other organizations also.

a. Magnitude of current-induced mooring forces

b. Magnitude of the current-induced buoy excursion and the mooring shape

c. Excursion extrapolation to different water depths

d. Effect of mooring pretension on buoy excursion

4.2 Mooring Configuration

The mooring configuration for the rubber band mooring is shown in Figure 1. It is made up of a rubber band section and an inelastic section that could be made up of synthetic line or wire rope. That section is considered inelastic and weightless so that it does not complicate elongation measurements of the rubber band section. The diameter is arbitrarily chosen as one inch.

The rubber band section consists of six 1-inch diameter filaments in parallel, having a length of 27 feet. These filaments are equally spaced around a 10-inch diameter ring which serves as a termination member. The spring constant of the rubber section, assumed to be 1200 pounds per foot per foot, was estimated from limited data that was available during the early phase of the materials investigation. The mooring configuration for this analysis was taken from the initial mooring design for the 8X26 buoy deployment at the Fishers Island test site.

The hull configuration of the 8X26 buoy is shown in Appendix A and the drag coefficients came from Reference 1.

4.3 Mooring Analysis Cases

4.3.1 Mooring Tension

The mooring tensions computed in this simulation were used to design the mooring for the deployment of the 8X26 buoy and to size the load cell that was placed in the mooring to record the mooring tension.

To determine the effect of current on the mooring tension, the computer program was exercised for Case R1 using current values of one, three and six knots. The mooring configuration and current cases are shown in Table 1.

4.3.2 Excursion and Mooring Shape

One of the sub-objectives of the 8X26 buoy deployment was to determine the buoy excursion by measuring the inclination (angle between the mooring and the horizontal) of the mooring at the top and calculating excursion from geometry. This method is valid only if the mooring is straight. The purpose of the computer simulation is to determine the shape of the mooring by calculating the inclination at several points along the mooring. If the inclinations are equal, the above method will apply; if they are not, the computed angles and excursions will be used to derive an alternate method. The computer calculates the angle at the anchor (Angle 1), the junction between the inelastic and rubber section (Angle 2), and angle at the buoy (Angle 3). (See Figure 1.)

4.3.3 Excursion Extrapolation

Another sub-objective of this simulation is to determine if the buoy excursion for a mooring in a depth of water can be used to predict the buoy excursion in another depth of water. If so, it might be possible to design a so-called "standard rubber band mooring(s)" and change only the length of the inelastic section to accommodate the depth of water and provide the necessary mooring pretension. Cases R1 and R3 (Table 1) simulate that situation. The inelastic section length is selected so that the pretension in the rubber section is the same in water depths of 50 feet and 125 feet. The computer program was exercised for current one and three knots.

4.3.4 Effect of Mooring Pretension on Buoy Excursion

Buoy excursion is a function of mooring pretension which is determined by the inelastic section length. Configuration Cases R1 and R2 have the same rubber band section length and water depth. The inelastic section in Case R2 has been shortened so that the mooring pretension is twice that in Case R1.

4.4 Computer Program

The computer simulation was performed using the DESADE computer program at the Naval Underwater Systems Center, New London, Connecticut. The DESADE program is based on the following assumptions:

a. The only hydrodynamic forces considered to be acting on the buoy is the drag force, since lift forces are considered negligible compared to the drag force and the buoy weight and buoyancy.

b. Only normal drag forces are considered to act on the mooring. Tangential drag forces are neglected.

c. The current is considered to be uni-dimensional and uniformly distributed over the entire length of the mooring.

4.5 Results

4.5.1 Excursion and Mooring Shape

The inclination of the mooring for Case R1 appears in Table 2 and the mooring profile is shown in Figure 2. The data indicates that the rubber band section is not a straight line for any of the current conditions tested; the inelastic section is, however, straight. This indicates that it is not possible to accurately calculate buoy excursion solely from the inclination at the top of the mooring (discussed in Section 4.3.2). An alternate method (derived in Appendix B) was developed from the data for Case R1. This method requires measuring the angle of the rubber section at the top and the bottom. The equation is:

$$E = L \cos \Theta_1 + \left(\frac{y - L \sin \Theta_1}{4} \right) \left(\frac{6}{\tan \Theta_3 + \tan \Theta_2} + \frac{1}{\tan \Theta_2} \right)$$

where: E = buoy excursion (distance between the buoy and the point on the water surface directly above the anchor).

L = length of the inelastic section (see Figure 1)

D = water depth

Θ_1 = acute angle between inelastic section and the horizontal

Θ_2 = acute angle between the horizontal and the tangent to the mooring at the junction of the inelastic section and the rubber band section (see Figure 1)

Θ_3 = acute angle between the horizontal and a tangent to the rubber section at the buoy

Appendix B shows the derivation of this expression as well as the difference between the excursion values shown in Table 2 and those calculated using the expression.

4.5.2 Mooring Tension

The mooring tensions for the 8X26 buoy in 50 feet of water (Case R1) is shown in Table 2. A tension of 1950 pounds is calculated for a current of three knots; based on preliminary design criteria developed during the materials tests, that tension is the limit of what the mooring can withstand. The tension at six knots, 5900 pounds, is not a realistic case because it is far beyond the capability of the mooring.

The mooring tension is a function of the square of the current. Figure 3 shows the square root of mooring forces for Cases R1 and R2 plotted against current. Both cases can be approximated by a straight line. It is interesting to note that the tension increases with the square of the current and that the excursion does not. Figure 4 shows that the slope of the square-root-of-excursion plot tends to decrease as the current increases; that means that the rate at which the excursion increases with current is declining as current increases. Figure 3 shows that the slope of the square-root-of-mooring force plot continues at the same slope as current increases. Because of the compliance of the mooring material, the current causes the mooring to become more curved (up to the working limit, three knots) and the tension increases (because of the increase in length) without the attendant increase in buoy excursion. This hypothesis can be tested by observing the difference between the inclination at the buoy (Figure 1, Angle 3) and the inclination at the junction (Angle 2). As the current increases from one to three knots, the difference between Angle 1 and Angle 3 increases indicating a greater curvature. At six knots the difference is not as great but the mooring is so elongated by buoy drag that it is almost horizontal and probably is not as affected by current. As discussed previously, the 6-knot current case is not realistic. If the six filaments could be replaced by one larger filament of equal cross sectional

area, the drag on the mooring would be less because the profile area would be smaller and the mooring would be stiffer because the section modulus would be greater. This should simplify the procedure of extrapolating buoy excursion from one current to another.

4.5.3 Excursion Extrapolation at Various Depths

Table 3 shows the ratio of excursion-to-depth that are taken from data presented in Table 2. It is seen that, for a given buoy and current, the ratios at different depths differ by 15 to 20 percent. It is concluded that, for the same mooring, extrapolation of excursion from one depth to another is possible (current held constant).

4.5.4 Effect of Mooring Pretension on Buoy Excursion

The mooring profiles for Cases R1 and R2 are shown in Figure 2 and Table 2. It is seen that, by increasing the pretension by 100 percent (from 355 pounds in Case R1 to 711 pounds in Case R2), the buoy excursion is decreased by 85 percent, 9 percent and 0 percent at currents of one, three and six knots, respectively. This illustrates the susceptibility of the rubber band mooring to current forces on a high-drag buoy. As the current increases, the moor tension increases and the pretension becomes a smaller portion of the moor tension; thus pretension has a reduced effect on the buoy excursion as current increases.

5.0 COMPARISON OF A NYLON MOORING AND RUBBER BAND MOORING ON AN 8X26 NAVIGATION BUOY AND AN 8-FOOT DIAMETER OSI BUOY

5.1 Objectives

The secondary objective of this simulation is to illustrate the effect of a rubber band mooring on the buoy excursion and mooring forces of an 8X26 buoy by comparing the rubber band mooring to a nylon mooring of conventional scope. The 8-foot diameter OSI buoy will also be used to illustrate how a low-drag buoy can be used to enhance the characteristic capabilities of rubber band mooring.

5.2 Mooring Configuration

The mooring configuration for the rubber band mooring is shown in Figure 1; it is identical to that described in Section 4.2. The nylon mooring (Figure 5) is composed of an arbitrarily selected 1-inch diameter, 2-in-1 double braided nylon line. It has a rated breaking strength of 28,500 pounds; the load-elongation curve and spring constants for that line appear in Appendix C.

5.3 Buoy Hull Configurations

The hull configuration and dimensions of the 8X26 and 8-foot diameter OSI buoys appears in Appendix A.

5.4 Computer Program

The computer program used in this portion of the simulation was developed by the Engineering Mechanics Staff at the Naval Underwater Systems Center, New London, Connecticut. The program is called the "towed cable program" (TCP) and was originally developed to determine the configuration of an oceanographic cable in a turn. It was extended to consider a broad group of static and dynamic cable problems. The DESADE Program (Section 4.4) is compared to the TCP Program in Appendix D. The major assumptions of this program are:

a. The only hydrodynamic forces considered to be acting on the buoy is the drag force, since lift forces are considered negligible compared to the drag force and the buoy weight and buoyancy.

b. Both the normal and tangential drag forces are considered to act on the mooring.

c. The current is considered to be uni-dimensional and uniformly distributed over the entire length of the mooring.

5.5 Computer Analysis Cases

The rubber band mooring configuration and current cases in Cases R1 and R3 (Table 1) are used. The 6-knot case is not included because it was found to be unrealistic (Section 4.5.2) for this mooring. The rubber sections of these two moorings are identical; the inelastic section is adjusted to provide the same pretension in 50 and 125 feet of water. The configuration and current cases of the nylon mooring appears in Table 4. The scope of 1 1/2:1 (Case N1 and N3) is selected for discussion because (a) that is probably the shortest scope that can be recovered in a manner similar to the conventional chain mooring (i.e. sufficient length to lift the buoy onto the deck, disconnect the buoy and attach the mooring to lifting machinery), and (b) that scope will result in a reduced excursion as does the rubber band and the excursions and mooring forces be compared directly. The scope of 3:1 (Cases N2 and N4) is similar to scopes that are used on conventional chain moorings.

Each case is run using the 8-foot diameter OSI buoy and the 8X26 buoy. The drag coefficients for the 8X26 buoy were taken from Reference 1.

5.6 Buoy Excursion

The results obtained from the cases described in Section 5.5 are shown in Tables 5 and 6. The excursions for both buoys on both types of moorings are plotted in Figures 6 and 7. The results indicate that the use of a rubber band mooring rather than a nylon mooring (1 1/2:1 scope) reduces the excursion of an 8X26 buoy in one knot of current by no less than 68 percent in water depths of up to 125 feet (Table 7). When the current is increased to three knots, the excursion of the rubber band mooring is only 8 percent less than that of the nylon mooring in 125 feet of water and approximately equal to the nylon mooring excursion in 50 feet of water.

If an 8-foot diameter OSI buoy, a low-drag buoy, is compared to an 8X26 buoy on the same moorings, Table 7 shows that, at one knot of current, the buoy excursion will be reduced by no less than 73 percent in water depths up to 125 feet. This represents a modest gain of 5 percent over the 8X26 buoy. At three knots of current, however, the excursion of the OSI buoy is approximately 34 percent and 15 percent less than the 8X26 buoy in 50 feet and 125 feet of water, respectively. The above observations illustrate (a) the susceptibility of the rubber band mooring to high drag forces, and (b) the reduction of the excursion achieved with a low-drag buoy.

Table 7 also shows the percent reduction in excursion when an 8-foot diameter OSI buoy with a rubber band mooring (a small-excursion buoy/mooring combination) is compared with an 8X26 buoy on a nylon mooring (conventional buoy/mooring configuration). The greatest excursion reductions are obtained in low current conditions.

5.7 Mooring Forces

The mooring tension results for the cases discussed in Section 5.5 appear in Tables 5 and 6 and Figures 8 and 9. The nylon mooring cases with a 1 1/2:1 scope is discussed because that scope will result in reduced buoy excursion as does the rubber band mooring (see Section 5.5).

It is observed that tension in the rubber band mooring on both the OSI and 8X26 buoys are between approximately 544-671 pounds (approximately 25 percent difference) in water depths of 50 feet and 125 feet and one knot of current. At three knots of current the tension in the 8X26 buoy mooring is as much as 32 percent above that of the OSI buoy.

The tension in the 8X26/nylon mooring is approximately 2 1/2 times greater than the OSI/nylon. Since there is no pretension associated with a nylon mooring, the tension differences are due solely to drag forces on the hull.

Table 7 shows the percent increase in mooring tension between a nylon mooring and a rubber band mooring on the OSI and 8X26 buoys. The mooring tension in a OSI/rubber mooring (one knot current/50 feet depth) is 666 percent greater than it is when a nylon mooring is used. At three knots of current the difference in tension of the nylon and rubber band mooring is reduced to 100 percent. This is due to the reduced proportion of total mooring tension that is pretension.

Table 7 compares the performance of the 8X26 buoy on a nylon mooring of 1 1/2:1 scope (conventional scope and buoy) with the OSI buoy on a rubber band mooring (low-drag buoy with taut mooring). The results show that OSI/rubber mooring combination has an excursion that is as much as 84 percent smaller than the 8X26/nylon mooring. At three knots of current, the difference between the two configurations is reduced to 23-33 percent. The reduction is due to the greater elongation of the rubber mooring at higher currents as will be discussed in Section 5.6.

The results also show that, while the tension is as much as 210 percent higher in the OSI/rubber band mooring at one knot, the tension difference between the two buoy/mooring configurations is decreased at higher currents and, in the 3 knot/50 foot water depth case (Cases N1-3 and R1-3), the tension in the 8X26/nylon mooring is actually 27 percent higher than the tension in the OSI/rubber band.

The results from Case R3-3 (Table 5) are not realistic because the elongation (3 1/2 times the original length) required to produce 2968 pounds of tension is outside the capability of the rubber material.

5.7.1 Effect of Rubber Band Mooring Tension on Sinker Weight Requirements

Since the rubber band mooring has a high vertical component of tension, the possibility of sliding the sinker along the bottom must be investigated. The theoretical relationship governing the maximum mooring tension capability of a sinker is discussed in Appendix E. The horizontal holding capacity of a concrete sinker has been experimentally determined to range between .45 (Reference 2) and 1.2 times the weight of the sinker in air (rock bottom and sand/mud bottom respectively). Using these holding power coefficients in the relationship derived in Appendix E, the maximum mooring tensions that can be applied to an 8500-pound concrete sinker can be computed.

The two curves in Figure 10 are the plot of the maximum holding capacity of an 8500-pound concrete sinker on a sand and a rock bottom as a function of the angle between the mooring and the horizontal. Individual data points of mooring tension/mooring angle are plotted that were computed for the 8X26/rubber band mooring (taken from Table 2). It is observed that in all cases except Case R3-3, the rubber band mooring tension is below the tension level at which the 8500-pound sinker will drag on either a sand or rock bottom. Since the point representing Case R3-3 is above "rock" curve and below the "sand" curve, it is concluded that the mooring tension in Case R3-3 is high enough to drag the sinker on a rock bottom but not high enough to drag on a sand bottom. (Cases R1-6 and R2-6 have already been disregarded because the high tension is unrealistic for that mooring configuration.) The 8X26/nylon mooring tensions are also shown in Figure 10 for comparison with those of the rubber band.

6.0 CONCLUSIONS

1. The computation of buoy excursion requires measuring the mooring inclination at the top and bottom of the rubber band section because that section deflects under the influence of current.

2. In currents of one knot the excursion of the 8X26 buoy on a nylon mooring (1 1/2:1 scope) can be reduced by as much as 73 percent by replacing the nylon with a rubber band mooring. At three knots of current the excursion is approximately equal.

3. The mooring tension in a rubber band mooring on an 8X26 buoy is as much as 222 percent greater than a nylon mooring (1 1/2:1 scope) at one knot of current. At three knots of current the rubber band mooring tension is only as much as 49 percent higher than the nylon mooring tension (Note 1).

4. The ability of the rubber band mooring to reduce buoy excursion is enhanced by the use of low-drag buoys and/or low currents (1 knot).

5. The deployment of the 8X26 buoy on this rubber band mooring is feasible in currents less than three knots and water depths less than 125 feet.

6. The excursion of a buoy on a rubber band mooring can be extrapolated from one water depth to another with an accuracy of 15 to 20 percent (assuming constant current).

7. The excursion of a buoy on a rubber band mooring cannot be extrapolated from one current condition to another by means of a simple relationship.

8. The use of a rubber band mooring on an 8X26 navigational buoy does not appear to require the use of sinker weight in addition to that normally used.

9. The tension in a rubber band mooring is proportional to the square of the current (for a constant water depth).

10. The excursion of an 8X26 buoy is reduced significantly (at one knot of current) by increasing the pretension. At three knots the effect of increased mooring pretension is negligible.

11. The excursion of a low-drag buoy like the 8-foot diameter OSI buoy deployed on a rubber band mooring is approximately 10 percent lower than the excursion of the 8X26 buoy (at one knot of current).

12. The tension in the OSI/rubber band mooring is as much as 210 percent higher than that in the 8X26/nylon mooring (one knot of current). At three knots of current, however, the tension is 27 percent higher in the 8X26/nylon mooring (Note 1).

NOTE 1: The higher tension in the rubber band mooring in the static condition is due primarily to the pretension. In a dynamic case, it is expected that, because of the high compliance of rubber, the tension in the rubber band mooring will be less than that of the nylon mooring.

TABLE 1

RUBBER BAND MOORING CONFIGURATION AND CURRENT CASES

CASE	CURRENT (KNOTS)	WATER DEPTH (FEET)	INELASTIC SECTION LENGTH (FEET)	RUBBER BAND SECTION LENGTH (FEET) (UNLOADED)	ELONGATION IN ELASTIC SECTION (NO CURRENT) (FEET)	ESTIMATE PRETENSION (NO CURRENT) (LB.)	TOTAL MOORING LENGTH (NO LOAD) (FEET)
R1-1	1	50	15	27	8	355	42
R1-3	3						
R1-6	6						
R2-1	1	50	7	27	16	711	34
R2-3	3						
R2-6	6						
R3-1	1	125	90	27	8	355	117
R3-3	3						

TABLE 2

8X26 NAVIGATIONAL BUOY MOORING DESIGN DATA

CASE	BUOY EXCURSION (FEET)	DEPTH BUOY SINKS (IN.)	MOORING TENSION (LBS.)	MOORING ANGLE		
				BUOY (3)	JUNCTION (2)	ANCHOR (1)
R1-1	20	1.64	530	80°	62°	61°
R1-3	68	6.64	1,950	61°	25°	25°
R1-6	162	11.64	5,900	30°	10°	10°
R2-1	13	2.64	810	84°	69°	69°
R2-3	62	7.64	2,150	68	27	27
R2-6	161	14.64	6,090	43°	10°	10°
R3-1	47	2.64	800	76°	63°	60°
R3-3	147	12.64	3,650	75°	32°	29°

TABLE 3

8X26 NAVIGATIONAL BUOY/RUBBER BAND MOORING
EXCURSION SCALE-UP RATIOS

BUOY	CASE	WATER DEPTH (FEET)	EXCURSION (FEET)	EXCURSION DEPTH
8X26	R1-1	50	20	.4
	R3-1	125	47	.376
	R1-3	50	68	1.36
	R3-3	125	147	1.17

TABLE 4

NYLON MOORING CONFIGURATION AND CURRENT CASES

CASE	CURRENT (KNOTS)	WATER DEPTH (FEET)	MOORING LENGTH (FEET)	SCOPE
N1-1	1	50	75	1 1/2:1
N1-3	3			
N2-1	1		150	3:1
N2-3	3			
N3-1	1	125	187	1 1/2:1
N3-3	3			
N4-1	1		375	3:1
N4-3	3			

TABLE 5

BUOY EXCURSION AND MOORING TENSION RESULTS FOR THE 8X26 NAVIGATIONAL BUOY WITH A RUBBER BAND AND A NYLON MOORING

CASE	BUOY EXCURSION (FEET)	DEPTH BUOY SINKS (IN.)	MOORING TENSION (LBS.)
R1-1	16.3	2.16	607
R1-3	67.3	5.76	2,110
R3-1	48.6	2.16	671
R3-3	139	10.56	2,968
N1-1	60	2.0	188
N1-3	66	4.56	1,900
N2-1	144	.96	169
N2-3	153	2.76	1,554
N3-1	147	2.16	217
N3-3	151	5.76	1,987
N4-1	359	.96	174
N4-3	381	2.16	1,581

TABLE 6

BUOY EXCURSION AND MOORING TENSION RESULTS FOR THE
8' DIA. OSI BUOY WITH A RUBBER BAND AND A NYLON MOORING

CASE	BUOY EXCURSION (FEET)	DEPTH BUOY SINKS (IN.)	MOORING TENSION (LB.)
R1-1	8.8	3.84	544
R1-3	44	7.4	1,384
R3-1	38.5	1.44	674
R3-3	114.7	12.2	2,261
N1-1	57.6	.56	71
N1-3	61	2.6	692
N2-1	143	.084	58
N2-3	147	1.0	533
N3-1	142	.44	83
N3-3	151	3.08	768
N4-1	355.8	.56	60
N4-3	364	1.64	558

TABLE 7

COMPARISON OF RUBBER BAND AND NYLON MOORING

	WATER DEPTH (FEET)	MOORING COMPARISON (1)				BUOY/MOORING COMPARISON (2)	
		OSI		8X26		OSI/RUBBER -VS-8X26/NYLON	
		1 KT	3 KT	1 KT	3 KT	1 KT	3 KT
EXCURSION REDUCTION (3) OF RUBBER OVER NYLON	50	84%	33%	73%	-1.5%	84%	33%
	125	73%	23%	68%	8%	75%	23%
TENSION INCREASE (4) OF RUBBER OVER NYLON	50	666%	100%	222%	11%	189%	-27%
	125	712%	194%	209%	49%	210%	13%

NOTES

(1) FOR EACH BUOY, VALUES OF TENSION AND EXCURSION ARE COMPARED FOR THE RUBBER BAND AND THE NYLON MOORING.

(2) VALUES OF TENSION AND EXCURSION FOR OSI BUOY WITH A RUBBER BAND MOORING COMPARED WITH 8X26 BUOY WITH NYLON MOORING.

(3) PERCENT REDUCTION IN SCOPE IF THE RUBBER BAND MOORING (CASE R1) IS USED IN PLACE OF THE NYLON MOORING (CASE N1): EXCURSION OF NYLON MOORING MINUS THE EXCURSION OF THE RUBBER BAND MOORING, DIVIDED BY THE EXCURSION OF THE NYLON MOORING

(4) THE PERCENTAGE BY WHICH THE TENSION IN A MOORING WILL BE INCREASED IF A RUBBER BAND MOORING (CASE R1) IS USED IN PLACE OF A NYLON MOORING (CASE N1): TENSION IN RUBBER BAND MOORING MINUS THE TENSION IN THE NYLON MOORING, DIVIDED BY THE TENSION IN THE NYLON MOORING

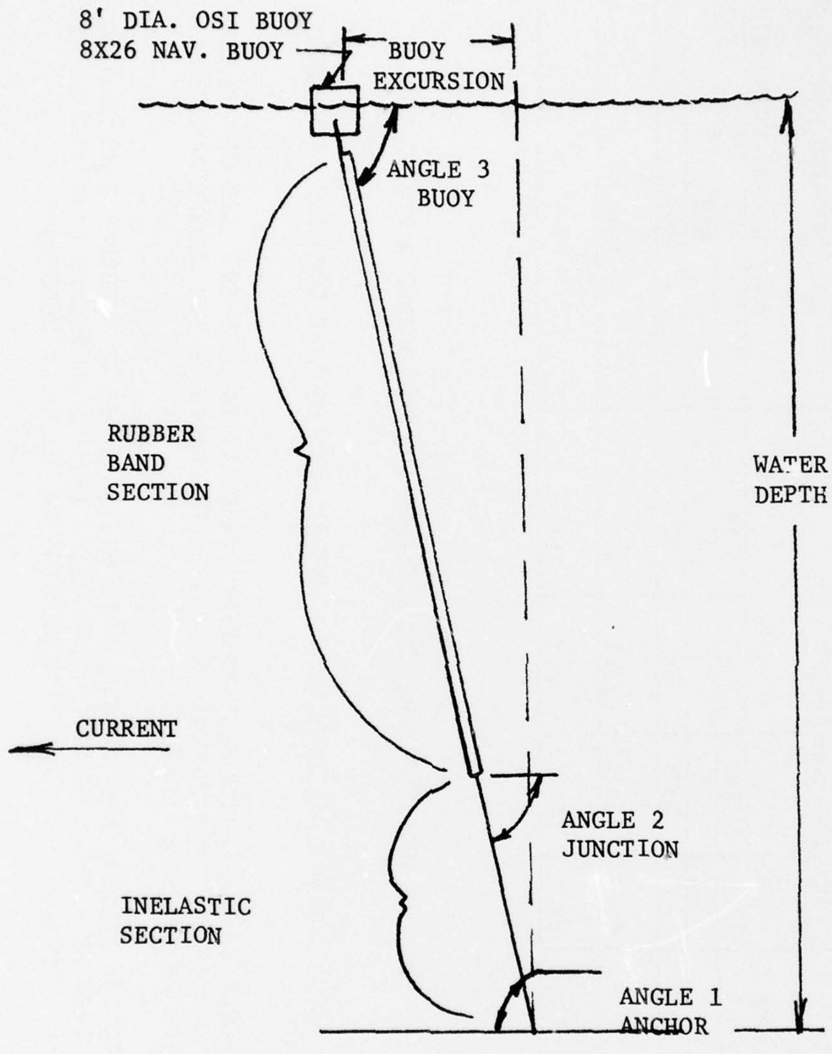
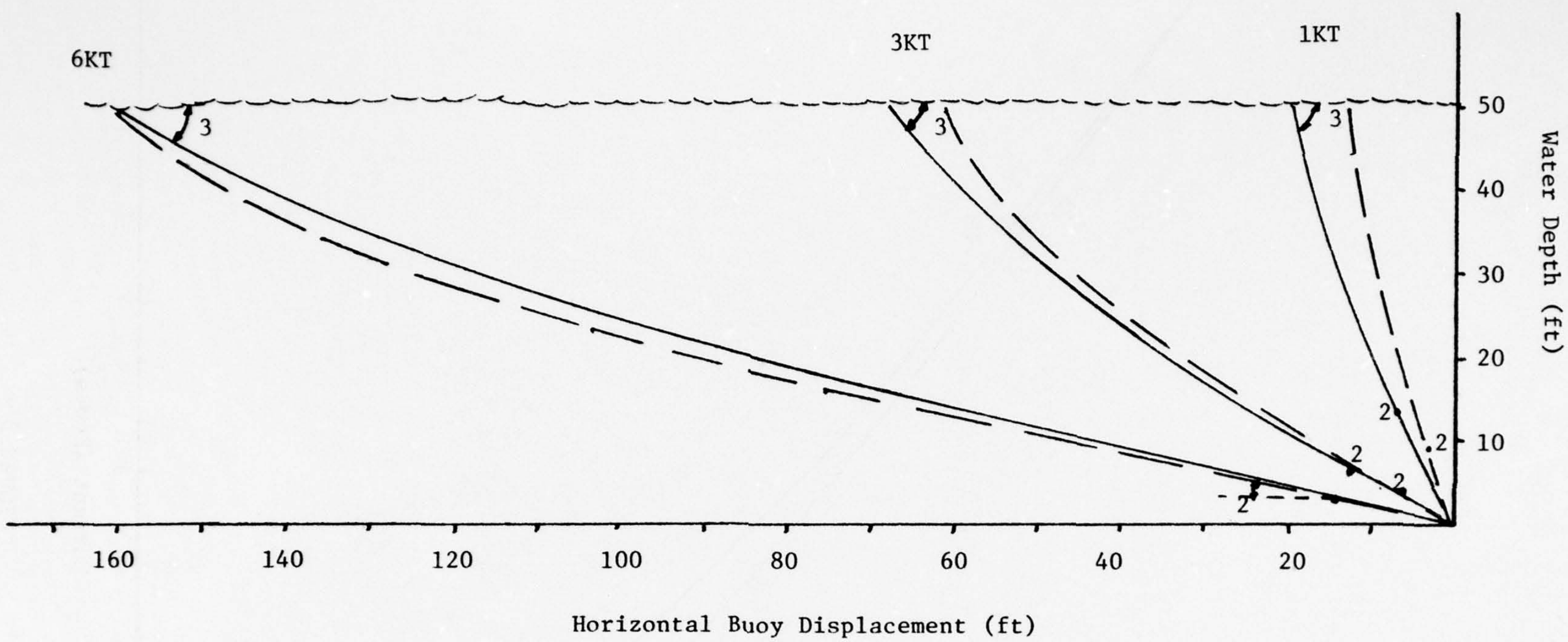


FIGURE 1

RUBBER BAND MOORING CONFIGURATION



Case R1: Solid Line
Case R2: Dashed Line

Buoy: 8X26 Nav. Buoy

FIGURE 2

MOORING PROFILE FOR CASES R1 and R2

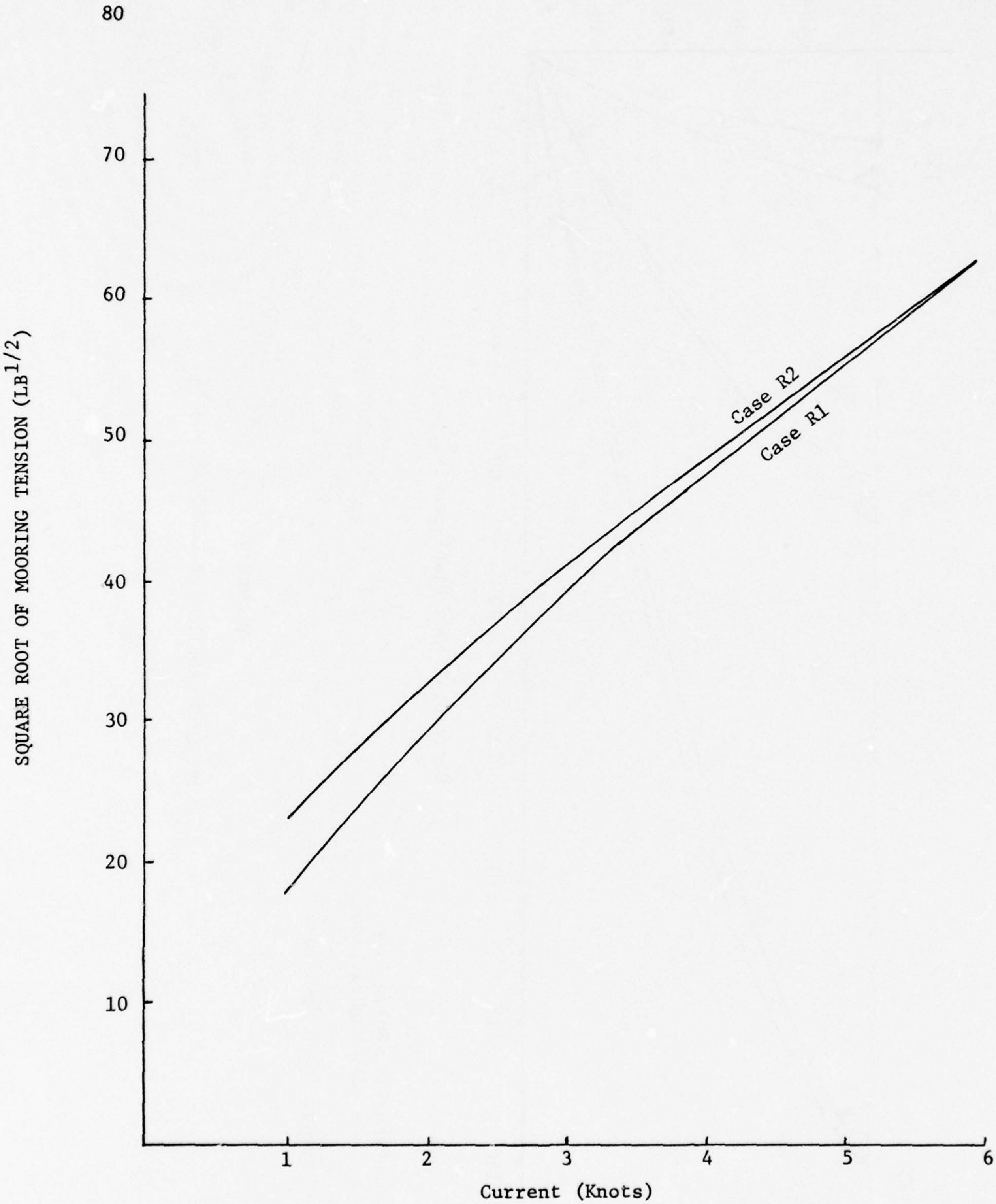


FIGURE 3

SQUARE ROOT OF MOORING TENSION VS. CURRENT FOR CASES R1 AND R2

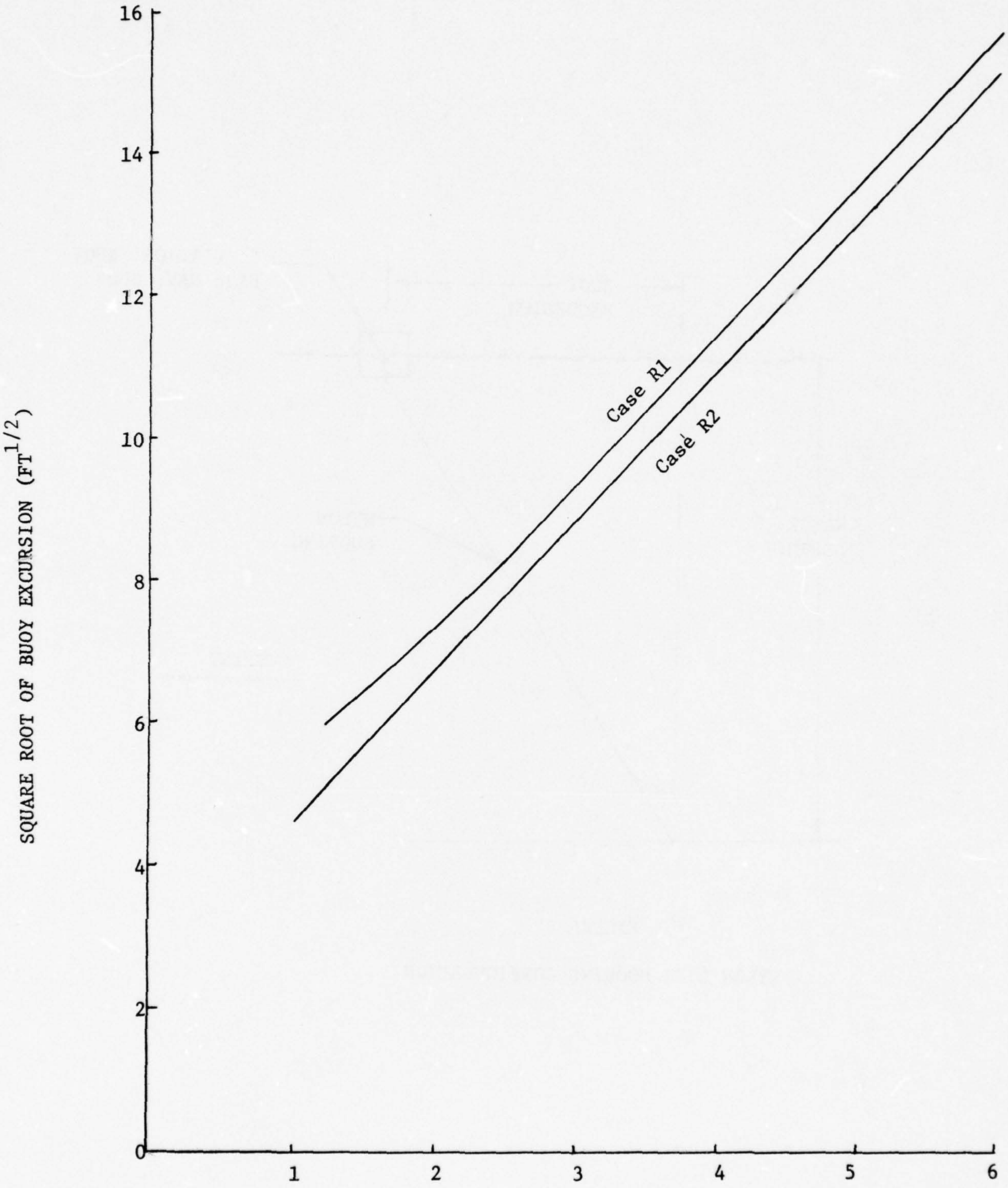


FIGURE 4

SQUARE ROOT OF BUOY EXCURSION VS. CURRENT FOR CASES R1 AND R2

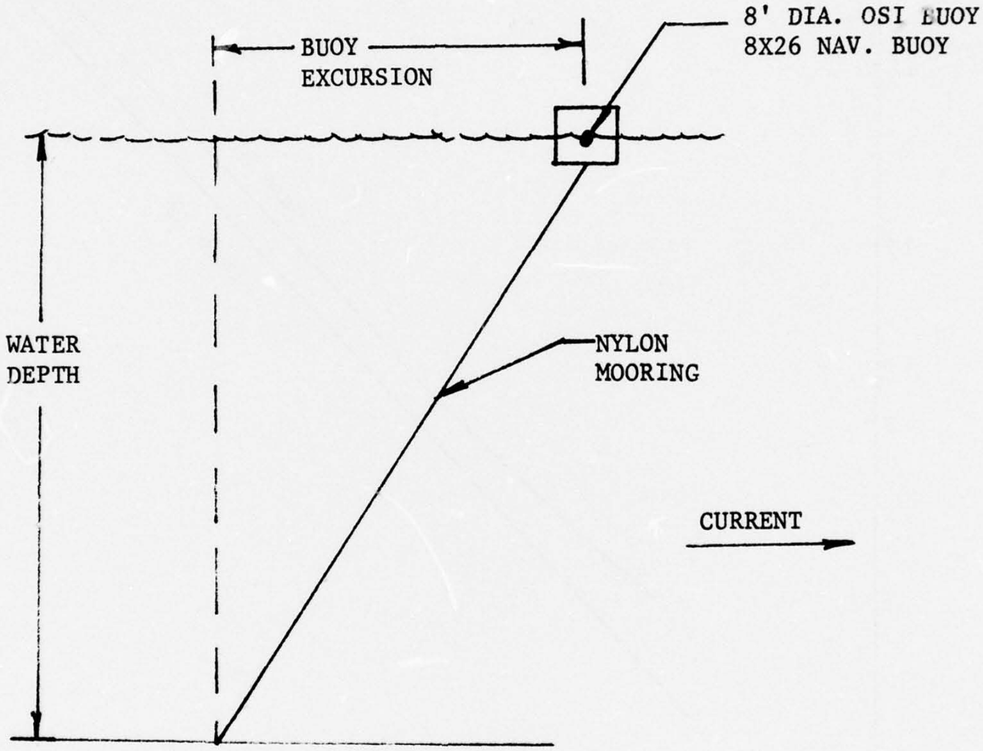


FIGURE 5

NYLON LINE MOORING CONFIGURATION

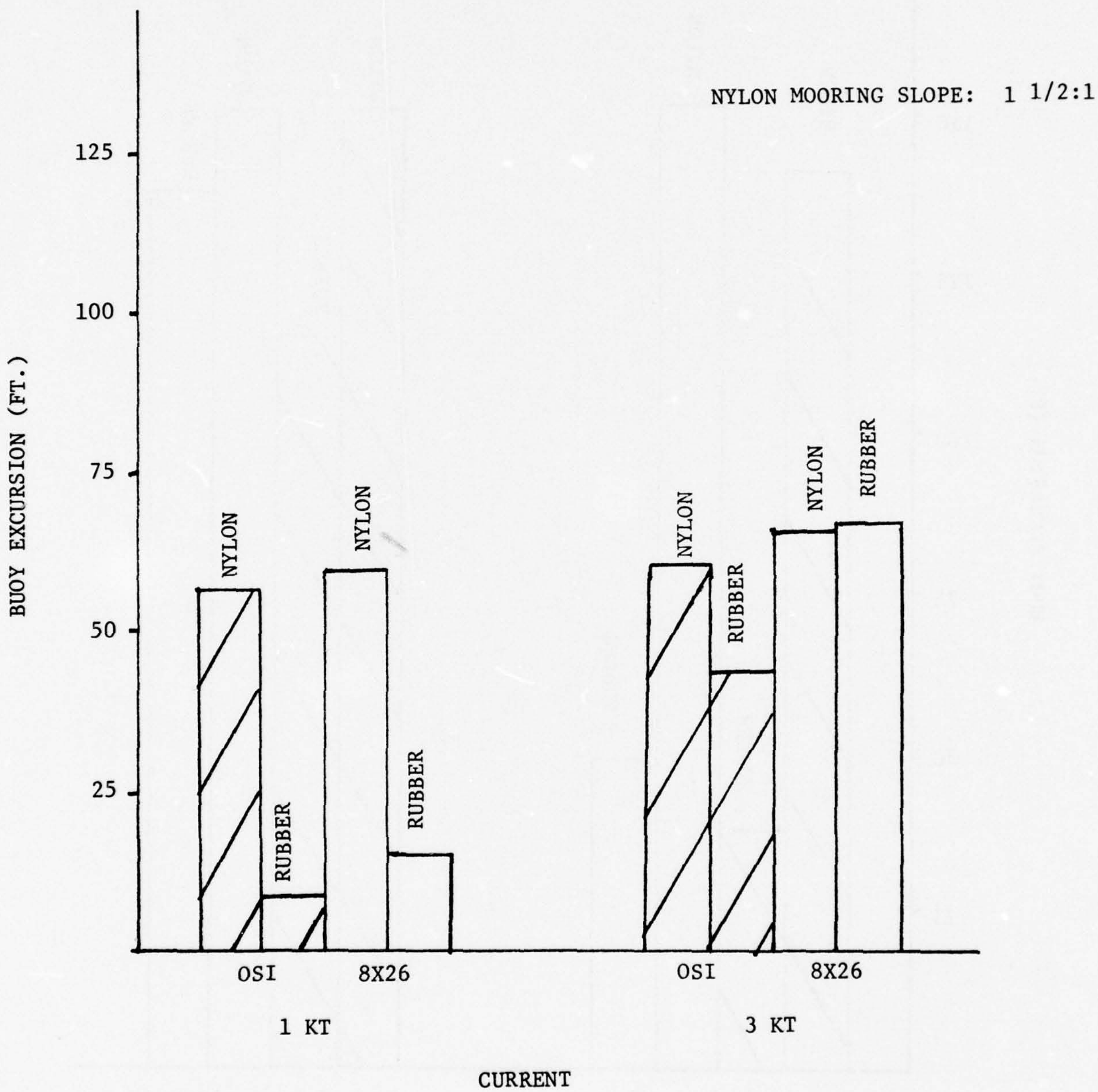


FIGURE 6

BUOY EXCURSION VS BUOY/MOORING IN

50 FEET OF WATER

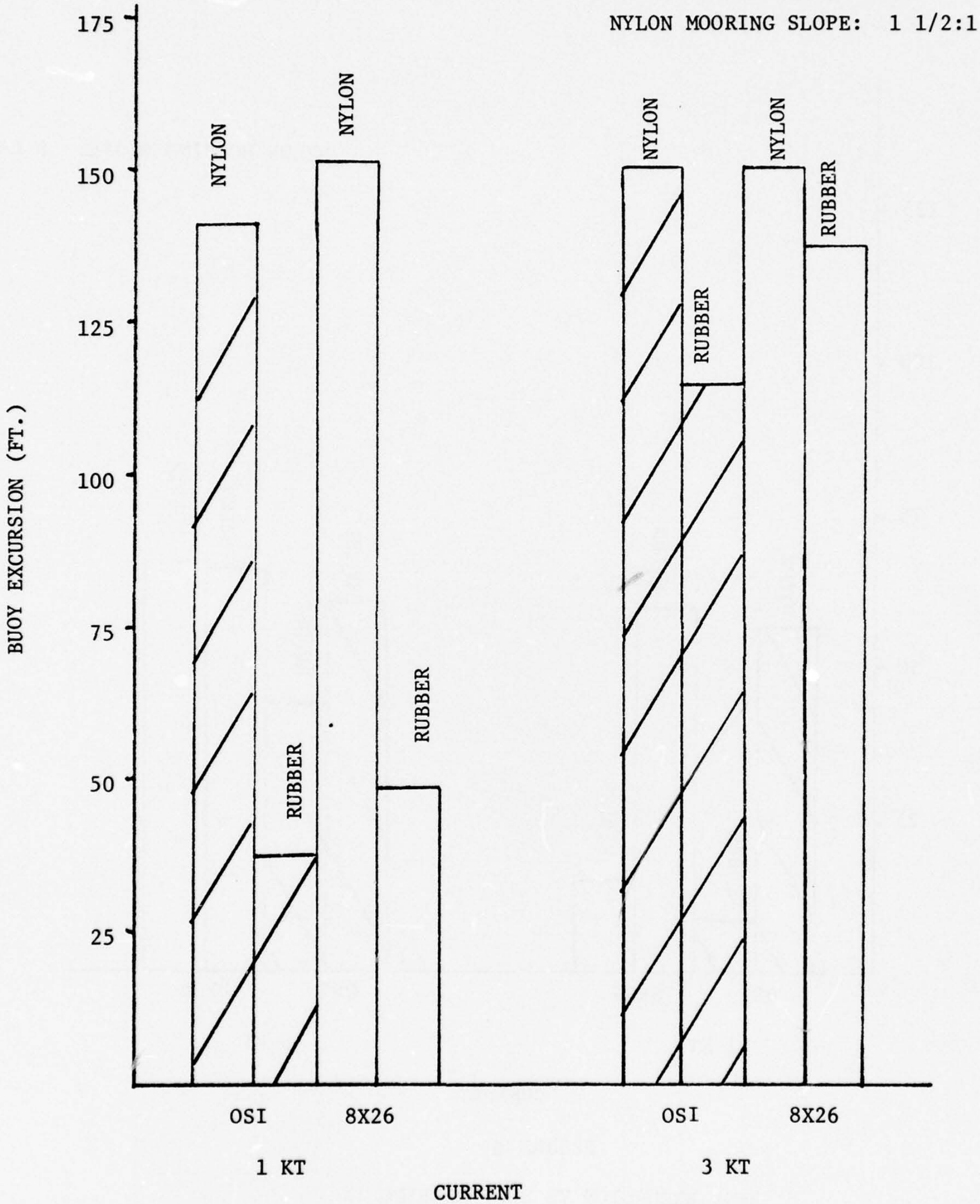


FIGURE 7

BUOY EXCURSION VS BUOY/MOORING IN 125
FEET OF WATER

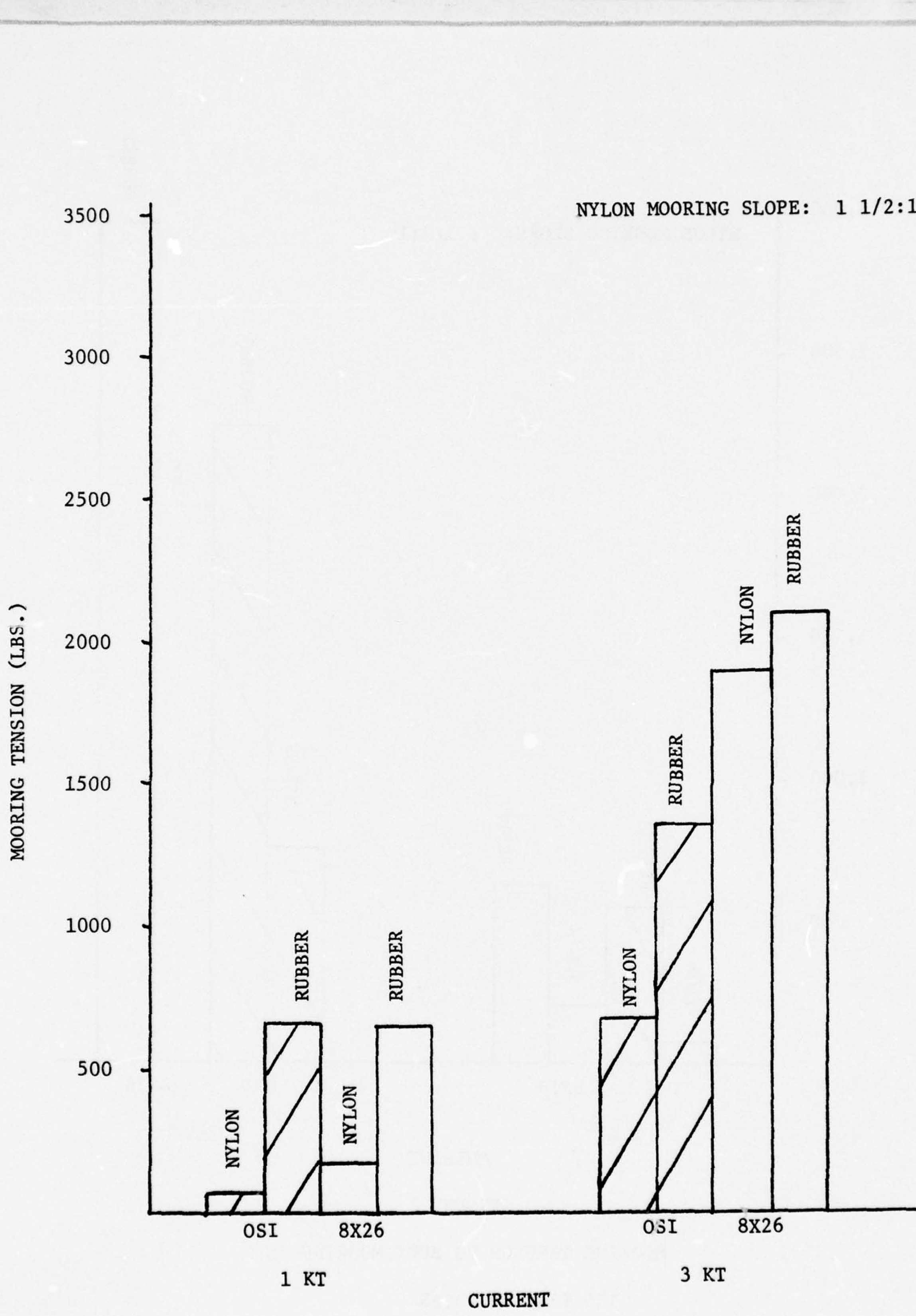


FIGURE 8

MOORING TENSION VS BUOY/MOORING IN

50 FEET OF WATER

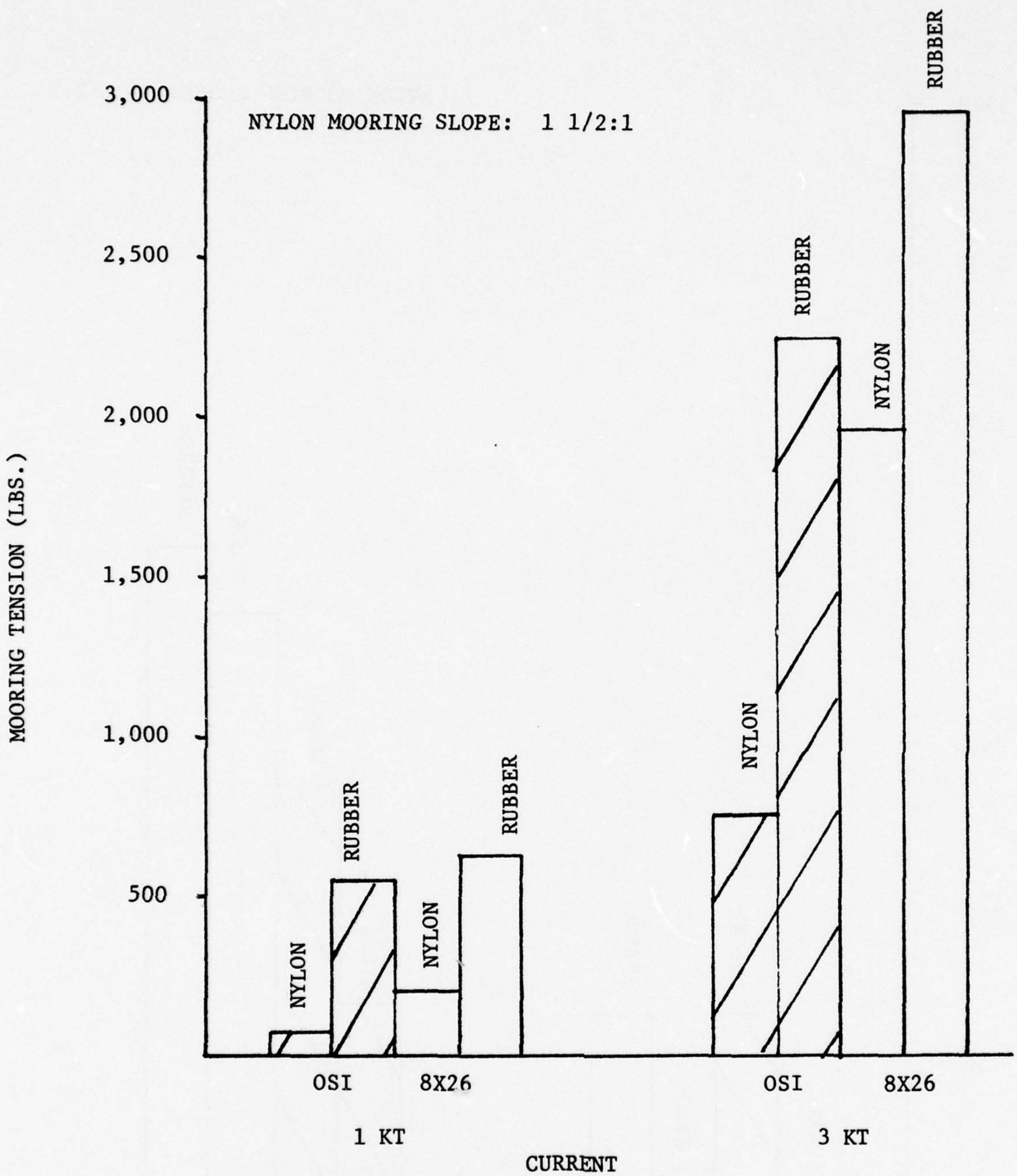


FIGURE 9

MOORING TENSION VS BUOY/MOORING IN

125 FEET OF WATER

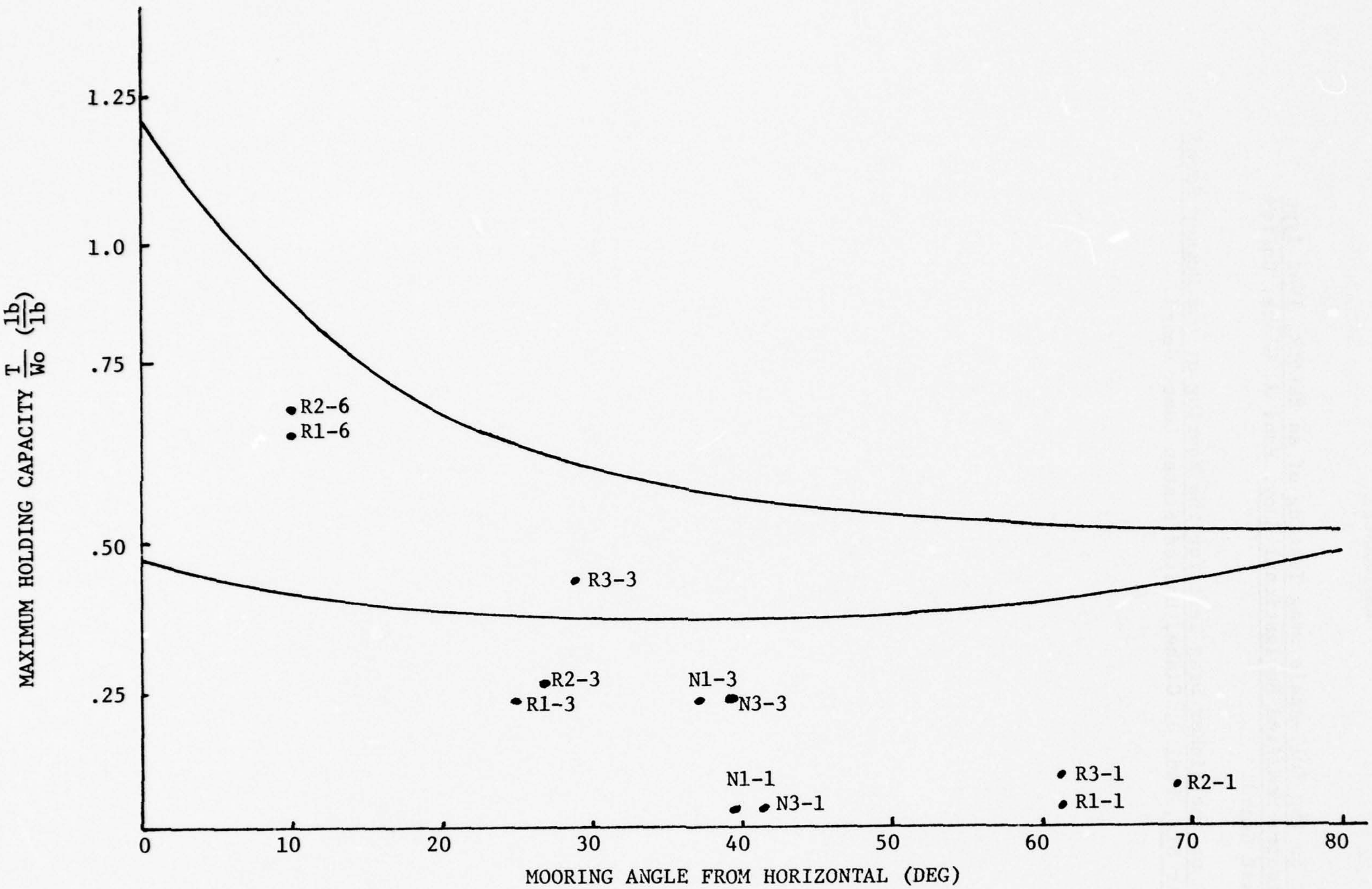


FIGURE 10

MAXIMUM HOLDING CAPACITY OF A CONCRETE SINKER AS A FUNCTION OF MOORING ANGLES

REFERENCES

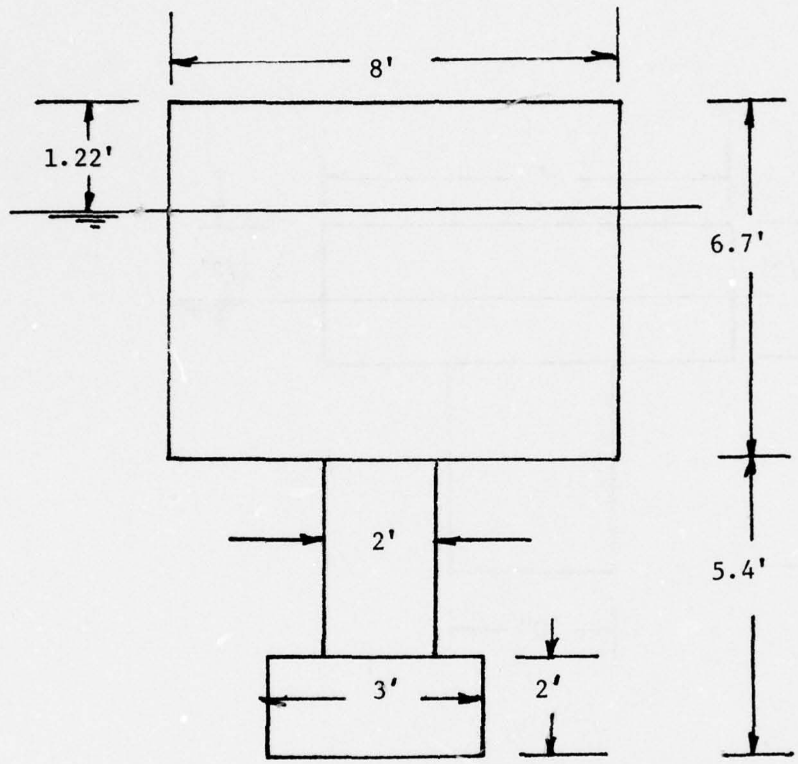
1. Report on the Full-scale Drag Testing of an 8XL6LR, 1942 Type Radar Reflector Modified Navigational Buoy, Paul J. Glahe, United States Coast Guard.

2. Report on the Sinker Drag Test for the Mooring of the Hussey Sound Buoy Number Six, Paul J. Glahe, United States Coast Guard.

APPENDIX A

BUOY HULL CONFIGURATION

8X26 NAVIGATION BUOY

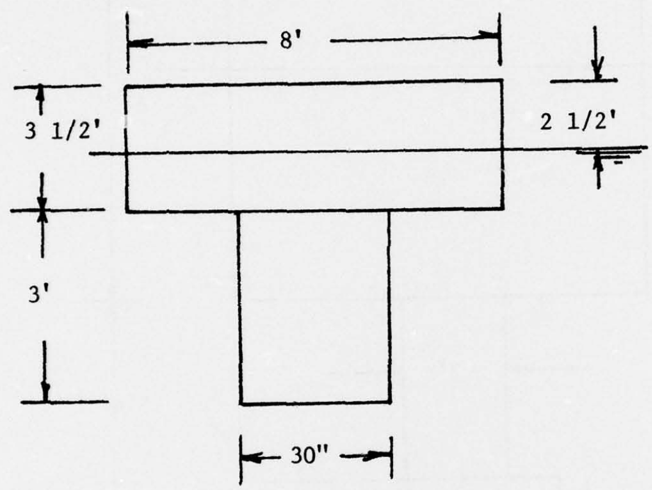


WEIGHT: 11,000 LBS.

RESERVE BUOYANCE: 260 LB./IN. (MAX. 14.75 INCHES)

MATERIAL: STEEL

OSI BUOY



WEIGHT: 3,200 LBS.

RESERVE BUOYANCY: 270 LB./IN.

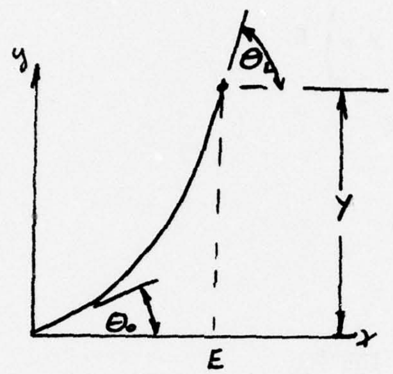
MATERIAL: POLYETHYLENE FOAM

APPENDIX B

8X26 NAVIGATIONAL BUOY EXCURSION EQUATION DERIVATION

To measure excursion of the 8X26 navigational buoy on the rubber band mooring described in Case R1 and R3 in Table 1, the mooring will first be assumed to be a parabola.

$$y = ax^2 + bx + c \tag{B-I}$$



the slope is

$$\frac{dy}{dx} = 2ax + b$$

The following boundary conditions are applied to obtain the constants a, b and c.

1. $y\big|_{x=o} = 0$, therefore $C = 0$ (B-II)

2. $\left.\frac{dy}{dx}\right|_{x=0} = b$ (B-III)

3. $\left.\frac{dy}{dx}\right|_{x=E} = 2aE + b$

$$a = \frac{\frac{dy}{dx_E} - \frac{dy}{dx_o}}{2E}$$

or

$$a = \frac{y'_E - y'_o}{2E} \tag{B-IV}$$

when

$$y'_E = \frac{dy}{dx_E} \quad \text{and} \quad y'_o = \frac{dy}{dx_o}$$

Substituting into equation (I) the constants as determined from equations (II), (III) and (IV), equation (I) becomes

$$y = \left(\frac{y'_E - y'_o}{2E}\right)x^2 + y'_o x$$

at $x = E$

$$y = \left(\frac{y'_E - y'_o}{2E}\right)(E)^2 + y'_o E$$

$$y \left(\frac{y'_E - y'o}{2E} + y'_o\right) E$$

$$= \left(\frac{y'_E + y'_o}{2}\right) E$$

Since $y'_E = \tan\ \Theta_L$

$y'_o = \tan \Theta_o$

$$E = \frac{2y}{\operatorname{Tan} \Theta_L + \operatorname{Tan} \Theta_o} \qquad \text{(B-V)}$$

where y = water depth

E = excursion of mooring at the surface

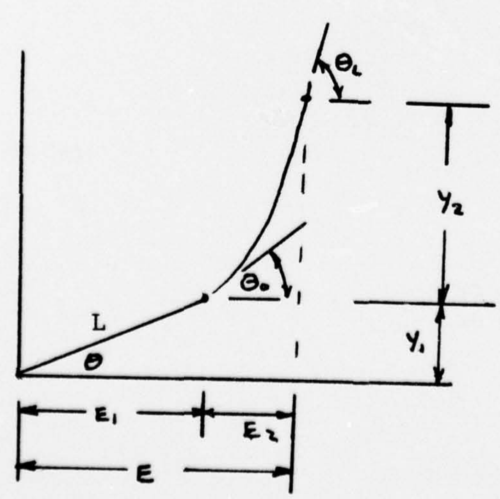
Θ_L = angle between the horizontal and a line tangent to the mooring at the surface

Θ_o = angle between the horizontal and a line tangent to the bottom of the mooring

Since the results in Table 7 show that the inelastic section is a straight line, the excursion of that section is $E_1 = L \cos \Theta$.

The excursion of the rubber band section is (equation (B-V)).

$$E_2 = \frac{2y_2}{\operatorname{Tan} \Theta_L + \operatorname{Tan} \Theta_o}$$



The total excursions

$$E = E_1 + E_2$$

$$= L \cos \Theta_o + \frac{2y_2}{\text{Tan } \Theta_L + \text{Tan } \Theta_o} \qquad \text{(B-VI)}$$

Since

$$y = y_1 + y_2$$

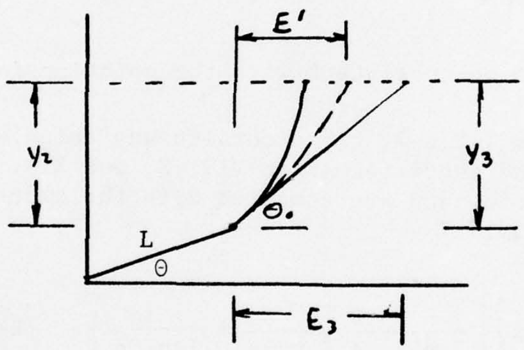
$$y = L \sin \Theta_o + y_2$$

$$y_2 = y - L \sin \Theta$$

Equation (VI) can be rewritten.

$$E = L \cos \Theta_o + \frac{2(y-L \sin \Theta)}{\text{Tan } \Theta_L + \text{Tan } \Theta_o} \qquad \text{(B-VII)}$$

When the mooring angles in Table 7 were used in equation B-VII, the excursion was consistently low. As a second approximation, it was assumed that the mooring is described by the average between the parabola and a straight line. By including the straight line, the excursion will be increased.



The excursion of the straight section (E_3) is

$$\Theta_o = \frac{y_3}{E_3}$$

$$E_3 = \frac{y_3}{\text{Tan } \Theta_o} \qquad \text{(B-VIII)}$$

Since $y_2 = y_3$

$$y_3 = y - L \sin \Theta_o \qquad \text{(B-IX)}$$

$$\therefore \quad E_3 = \frac{y-L \sin \Theta}{\text{Tan } \Theta_o}$$

Since the excursion of the rubber band section (E') is assumed to be the average of a parabola (E_2) and a straight line (E_3),

$$E' = \frac{E_2 + E_3}{2}$$

$$= 1/2 \left(\frac{2(y - L \sin \Theta)}{\operatorname{Tan} \Theta_L + \operatorname{Tan} \Theta_o} + \frac{(y - L \sin \Theta_o)}{\operatorname{Tan} \Theta_o} \right)$$

Then total excursion (E) is the sum of the inelastic section excursion (E_1) and the rubber band section excursion (E'),

$$E = E_1 + E'$$

$$= L \cos \Theta_o + \left(\frac{y - L \sin \Theta_o}{2} \right) \left(\frac{2}{\operatorname{Tan} \Theta_L + \operatorname{Tan} \Theta_o} + \frac{1}{\operatorname{Tan} \Theta_o} \right) \quad \text{(B-X)}$$

A third approximation of the excursion is the average between the parabola and parabola-straight line (called second average). That expression (arrived at similarly) is

$$E = L \cos \Theta_o + \left(\frac{(y - L \sin \Theta)}{4} \right) \left(\frac{6}{\operatorname{Tan} \Theta_L + \operatorname{Tan} \Theta_o} + \frac{1}{\operatorname{Tan} \Theta_o} \right) \quad \text{(B-XI)}$$

Equation B-XI can be rewritten to be consistent with the notation in Figure 1.

Using the mooring slope data from Table 7, the excursion was calculated using the three approximations discussed above (equation VII, X, and XI). Those results are shown in the table below and are compared with the excursion calculated by the computer program.

$$E = L \cos \Theta_1 + \left(\frac{y - L \sin \Theta_1}{4} \right) \left(\frac{6}{\operatorname{Tan} \Theta_3 + \operatorname{Tan} \Theta_2} + \frac{1}{\operatorname{Tan} \Theta_2} \right) \quad \text{(B-XIA)}$$

where: E = buoy excursion (distance between the buoy and the point on the water surface directly above the anchor)

L = length of the inelastic section (see Figure 1)

D = water depth

Θ_1= angle between inelastic section and the horizontal

Θ_2= acute angle between the horizontal and the tangent to the mooring at the junction of the inelastic section and the rubber band section (see Figure 1)

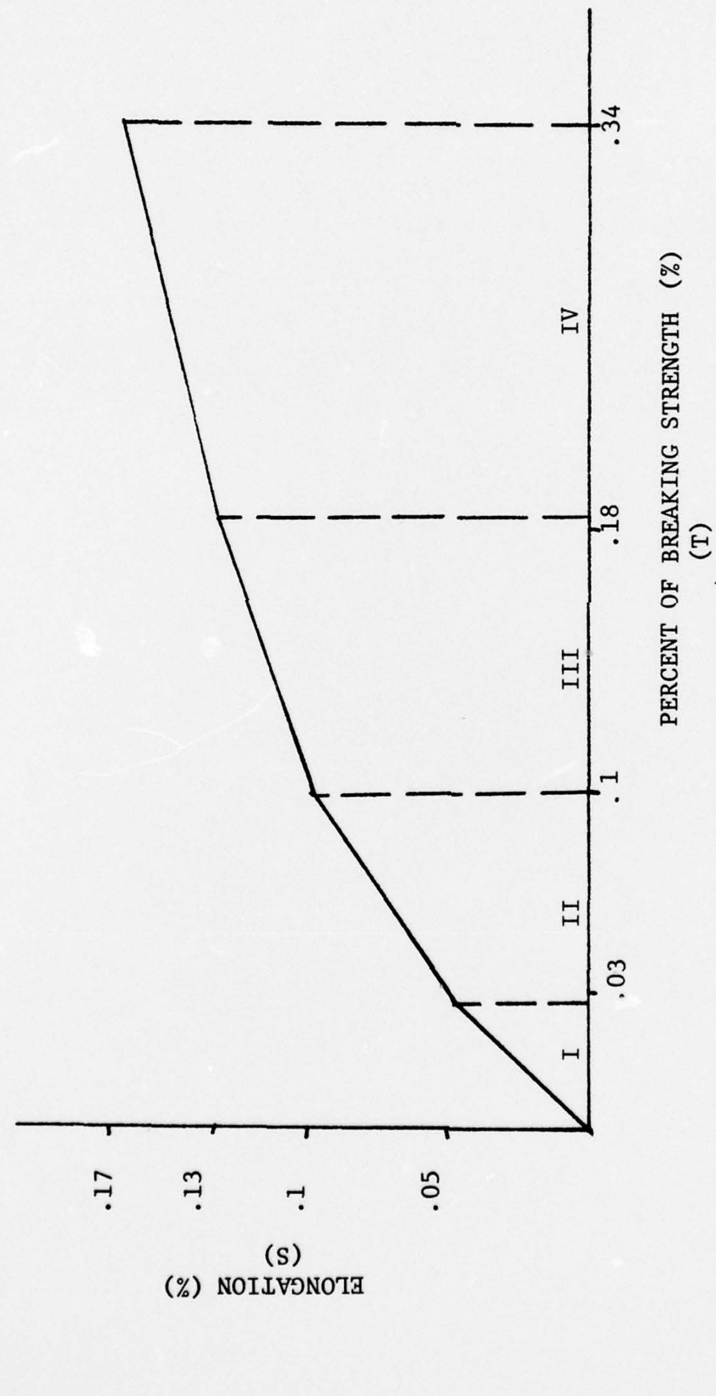
Θ_3= acute angle between the horizontal and a tangent to the rubber section at the buoy

BUOY EXCURSION

CASE	PARABOLIC EQUATION VII (FEET)	PARABOLIC - STRAIGHT LINE EQUATION X (FEET)	SECOND AVERAGE EQUATION XI (FEET)	COMPUTER CALCULATED (FEET)	DIFFERENCE BETWEEN COMPUTER AND SECOND AVERAGE
R1-1	17.3	21.86	19.46	20	2.7%
R1-3	50.8	79	64.5	68	5.1%
R2-1	6.09	13.7	9.89	13	23%
R2-3	37.85	67.8	52	62	16%
R3-1	55	60	57	47	10%
R3-3	11[illegible]	174	145	147	1.3%

APPENDIX C

LOAD - ELONGATION CURVE FOR 1" DIA. 2-IN-1 DOUBLE BRAID NYLON LINE



MAX. TENSILE STRENGTH: 28,500 LBS

FOR $S<.05$ $T = .6S$

$.05<S<.1$ $T = 1.4S-.04$

$.1<S<.13$ $T = \frac{8}{3}S - \frac{.5}{3}$

$.13<S<.17$ $T = 4S - .34$

REGION	SPRING CONSTANT (k) 10^4 (lb/in/in)
I	1.71
II	3.99
III	7.6
IV	11.4

APPENDIX D
COMPARISON OF DESADE AND TCP MOORING SIMULATION RESULTS

CASE	DESADE (3)		TCP (2)		DIFFERENCE (1)	
	EXCURSION	TENSION	EXCURSION	TENSION	EXCURSION	TENSION
R1-1	20	530	16	671	+20%	-26%
R1-3	68	1,950	67	2,110	+1.4%	-8%
R3-1	47	800	48	607	-2%	+24%
R3-3	147	3,650	139	2,968	+5%	+18.6%

NOTES:

(1) DESADE PROGRAM IS USED AS THE BASIS FOR COMPARISON.
PLUS SIGN INDICATES THAT DESADE VALUE IS HIGHER THAN TCP VALUE.

(2) RESULTS FROM TABLE 3.

(3) RESULTS FROM TABLE 7

APPENDIX E
THE EFFECT OF CHAIN ANGLE ON SINKER DRAG FORCE

A concrete sinker will fail to hold when the tension and mooring angle are such that the sinker either lifts off the bottom or begins to slide along the bottom. To determine which mode of failure predominates, equations of static equilibrium are written for the sinker and the interrelationship of the tension (T), the horizontal resistance coefficient (K_1), vertical resistance coefficient (K_2), and mooring angle (Θ) where W_w equals the weight of the sinker in water.

The horizontal forces at the sinker are:

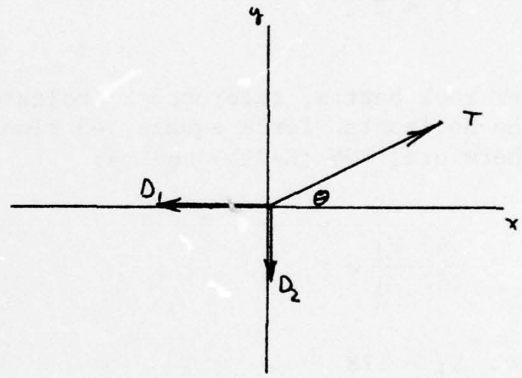
$$\Sigma F_x = D + T \cos \Theta$$

where $D = K_1 F_y$

The vertical forces are

$$\Sigma F_y = T \sin \Theta - K_2 W_w \qquad \text{(E-I)}$$

When the sinker starts to drag, the horizontal drag force is equal to the horizontal component of tension.



Therefore, $D = T\cos \Theta$.

Since $D = K_1 F_y$

$$K_1 F_y = T\cos \Theta$$

$$K_1(T \sin \Theta - K_2 W_w) = T\cos \Theta$$

$$T\sin \Theta \, K_1 - T\cos \Theta = K_1 K_2 W_w$$

$$T\,(K_1 \sin \Theta - \cos \Theta) = K_1 K_2 W_w$$

$$\frac{T}{W_w} \quad \frac{K_1 K_2}{K_1 \sin \Theta - \cos \Theta} \qquad \text{(E-II)}$$

At $\Theta = 90°$; EQN (E-I) becomes

$$\Sigma F_y = T - K_2 W_w$$

Under conditions where sinker movement is imminent,

$$\Sigma F_y = 0$$

and

$$\frac{T}{W_w} = K_2 \qquad \text{(E-III)}$$

The next step is to determine the horizontal resistance coefficient, K_1. It has been determined experimentally (reference 2) that the sinker will drag on a sand bottom at a horizontal tension ($\Theta = 0$) equal to 1.2 times the dry weight of the sinker.

For concrete $W_w = .57\ W_d$

$$W_d = \frac{W_w}{.57} \qquad \text{(E-IV)}$$

where W_w = weight of the concrete sinker in water

W_d = weight of the concrete sinker in air

At $\Theta = 0$, EQN (E-IIA) becomes

$$\frac{1.2\ W_d}{.57\ W_d} = \frac{K}{1}$$

$$K_1 = 2.1$$

For rock bottom, reference 2 indicates that the sinker will drag when the horizontal force equals .45 times the dry weight of the sinker. Therefore, EQN (E-IIA) becomes

$$\frac{.45\ W_d}{.57\ W_d} = K_1$$

$$K_1 = .78$$

To rewrite EQN (E-IIA) in terms of the horizontal component of tention (T_h)

$$\cos\Theta = \frac{T_h}{T}$$

$$\frac{T_h}{\cos\Theta\ (W_w)} + \frac{K_1}{\cos\Theta + K_1 \sin\Theta}$$

$$\frac{T_h}{W_w} = \frac{K_1}{1 = K_1\ \mathrm{Tan}\ \Theta} \qquad \text{(E-V)}$$

At that condition, K_2 must equal one because (excluding suction, etc.) the tension must equal tye sinker wet weight (W_w).

At $\Theta = 0$ (Equation E-II) the tension on the mooring (T) is equal to the horizontal holding power of the sinker (T_h). Therefore Equation E-II can be rewritten (assuming $K_2 = 1$)

$$\frac{T_h}{W_w} = \frac{K_1}{-1}$$

The horizontal resistance coefficient K_1 is observed to have a negative sign; Equation E-II will be changed to reflect that.

$$\frac{T}{W_w} = \frac{K_1}{\cos\Theta + K_1 \sin\Theta} \qquad \text{(E-IIA)}$$

To establish which failure mode will occur first (i.e., lifting the sinker or sliding the sinker), Equation E-I and Equation E-IIA are investigated. The sinker will drag when

$$\frac{T}{W_w} > \frac{K_1}{\cos\Theta + K_1 \sin\Theta}$$

The sinker will lift when

$$\frac{T}{W_w} > \frac{K_2}{\sin\Theta}$$

If suction is neglected, K_2 can never be greater than 1 because, at $\Theta = 90°$, the tension cannot exceed the wet weight of the sinker. The two equations for horizontal and vertical resistance forces are plotted in Figure E-1 for various values of K_1 and K_2. It is seen that the family of curves representing the horizontal forces is always below the curve presenting the vertical force condition. Therefore, for any mooring angle, Θ, the maximum horizontal force will be reached before the maximum vertical force and the sinker will drag rather than lift.

Using Equation (E-IV), Equation (E-V) and (E-IIA) can be converted to dry sinker weight.

$$\frac{T_h}{W_d} = \frac{.57\ K_1}{1 + K_1 \operatorname{Tan}\Theta} \qquad \text{(E-VI)}$$

$$\frac{T}{W_d} = \frac{.57\ K_1}{\cos\Theta + K_1 \sin\Theta} \qquad \text{(E-VII)}$$

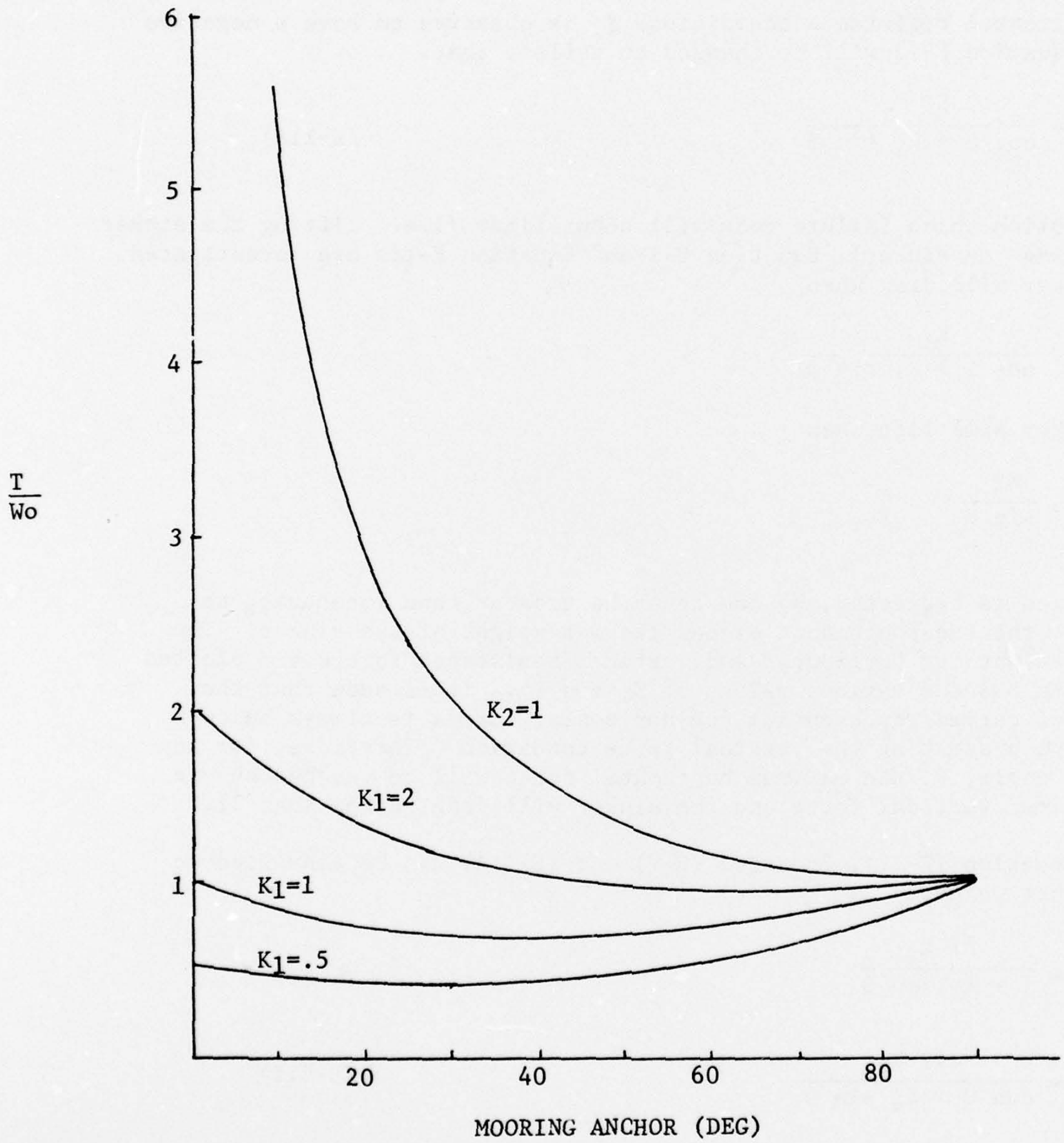


FIGURE E-1

HORIZONTAL AND VERTICAL RESISTANCE COEFFICIENTS

Substituting in the appropriate value of K_1 into Equation (E-VI) and (E-VII) for SAND

$$T = \frac{1.2\ W_d}{\cos\Theta + 2.1\ \sin\Theta} \qquad \text{(E-VIII)}$$

$$T_h = \frac{1.2\ W_d}{1 + 2.1\ \mathrm{Tan}\ \Theta} \qquad \text{(E-IX)}$$

For rock,

$$T = \frac{.45\ W_d}{\cos\Theta + .78\ \sin\Theta} \qquad \text{(E-X)}$$

$$T_h = \frac{.45\ W_d}{1 + .78\ \mathrm{Tan}\ \Theta} \qquad \text{(E-XI)}$$

The above equations are plotted in Figure E-2.

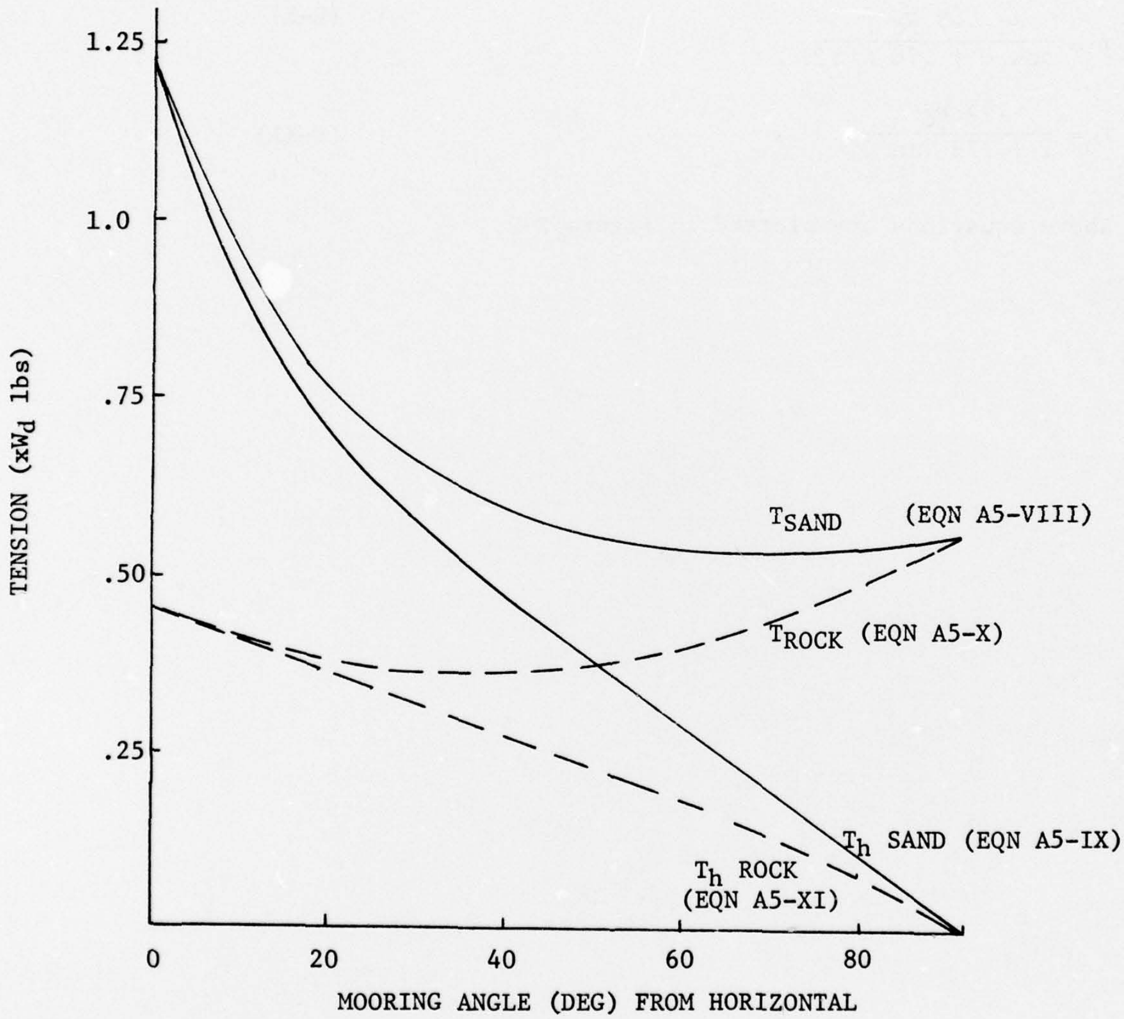


FIGURE E-2

MOORING TENSION VERSUS MOORING ANGLE

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